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CARBONDALE

Passive Treatment of Coal-mine Drainage by a Sulfate-reducing Bioreactor in the Illinois Coal Basin[1]

Paul T. Behum[2]; Liliana Lefticariu[3]; Evan Walter[3]; and Ron Kiser[4];

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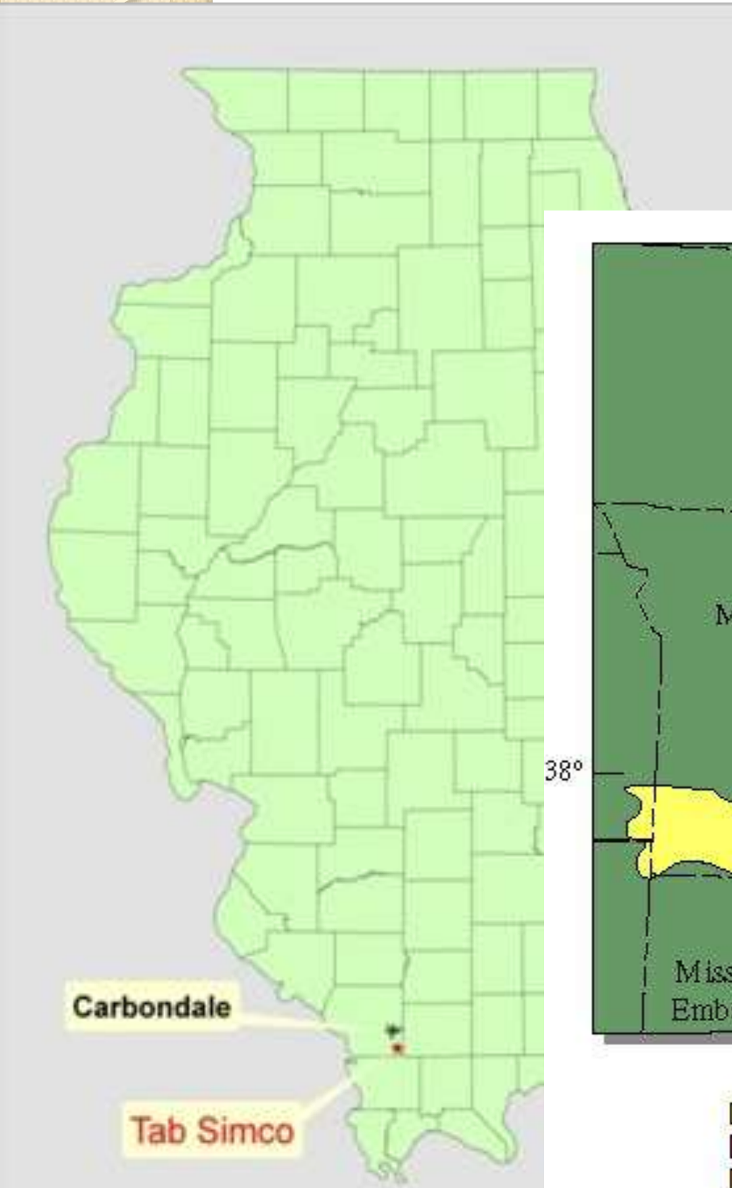
[2] Office of Surface Mining Reclamation and Enforcement and Environmental Resources and Policy Program, Southern Illinois University Carbondale., IL 62901, USA

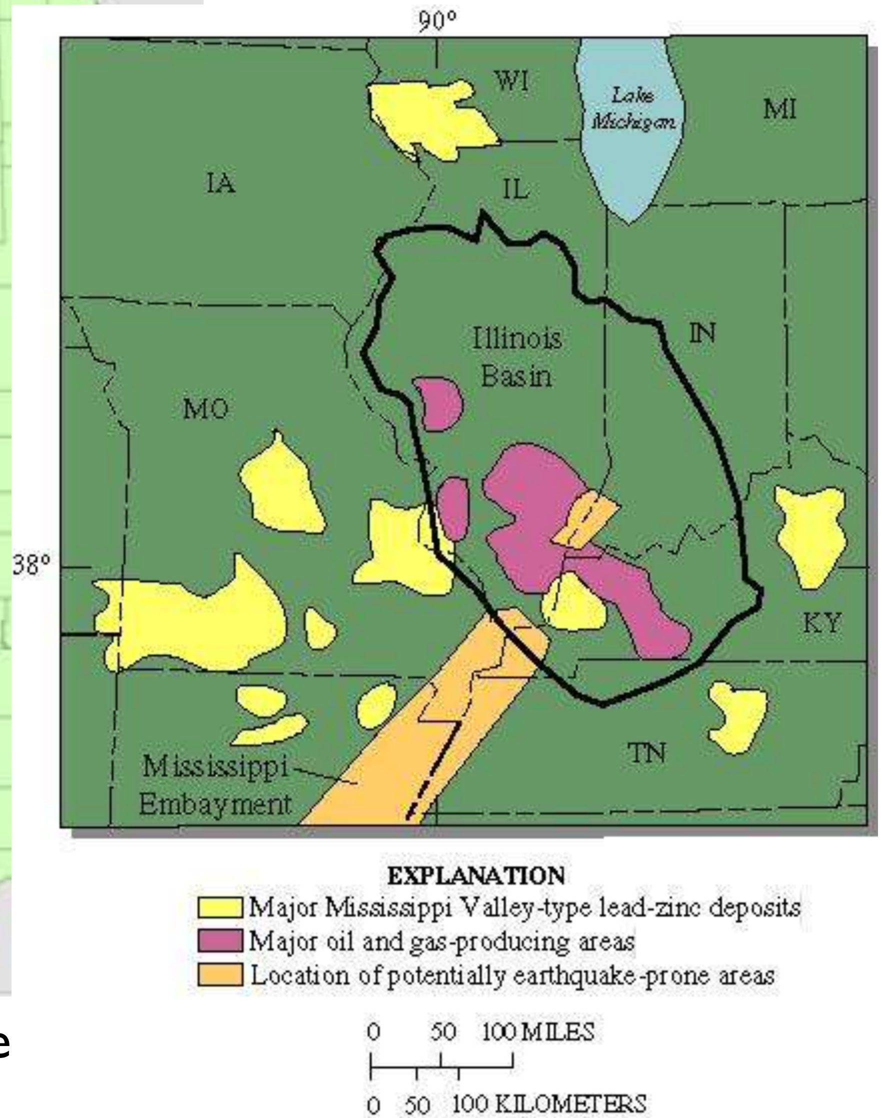
[3]Department of Geology, Southern Illinois University, Carbondale, IL 62901, USA.

[4]Illinois Department of Natural Resources, Office of Mines and Minerals, Benton, IL 62812, USA

Case Example Site Location



Tab-Simco Site Map Location.



Source: U.S. Geological Survey

Tab-Simco is an abandoned coal mine located in the Illinois Basin 3.2 km southeast of Carbondale, Illinois, USA.

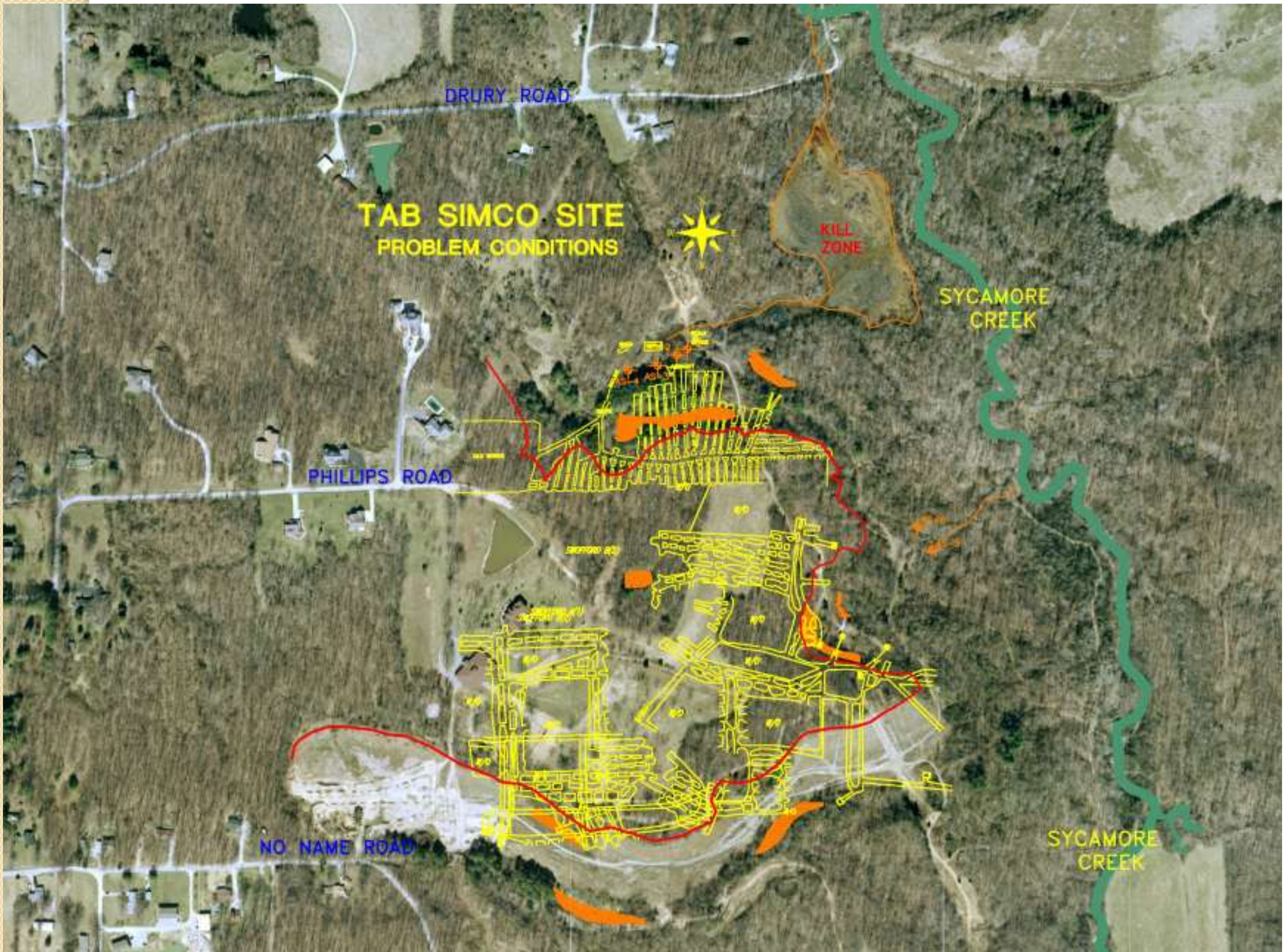
Geology of the Project Area

- Geologic Setting: Located on a dissected, low plateau underlain by coal-bearing Pennsylvanian System.
- Surficial Geology: Plateau areas are capped by 1 to 21 meter thick mantle of unconsolidated glacial till of the Illinoian Glasford Formation.
- Shallow Bedrock: A series of sandstone, shale, siltstone, claystone and coal of the Spoon Formation and underlying Abbot Formation.

Coal Mining History

- Underground Mining: Between the 1890's and early 1955 mined - the 2.5 m (8.2 ft) thick Murphysboro Coal and the overlying discontinuous 0-1.5 m (4.9 ft) thick Mt. Rorah Coal.
- Surface Mining: Contour-type surface mining bt the Tab and SIMCO coal companies during the 1960-s and 1970's in a horseshoe-shaped pattern removed coal in the outcrop barrier and "daylighted" some of the old underground workings.

Tab-Simco Underground Mine Workings

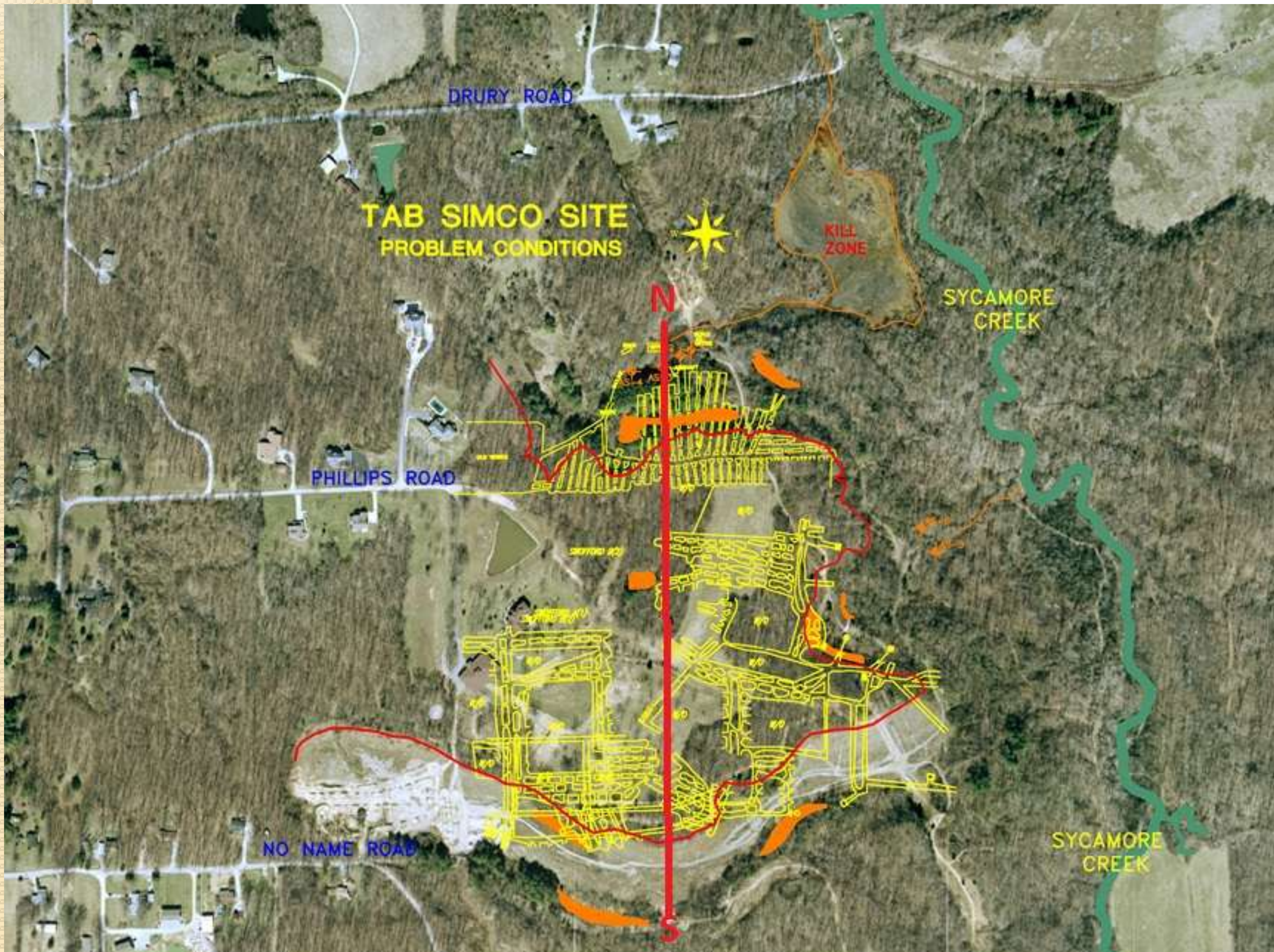


Source: J. Nawrot, SIUC, Unpublished Personal Communication, 2005.

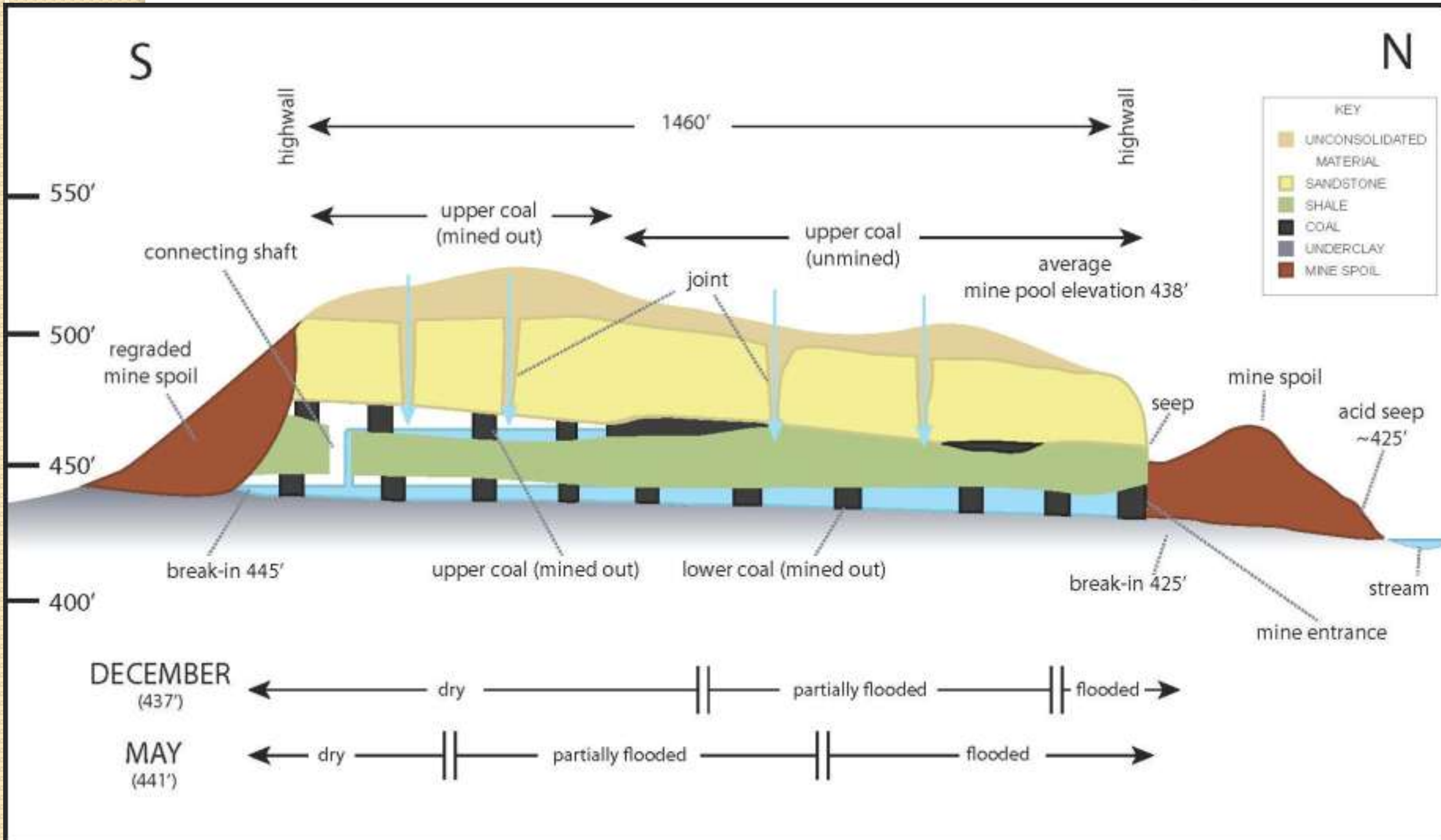
Tab-Simco Problem Identification:

- Mine Pool: The old underground workings are partially flooded with seasonal fluctuations and contains 40,000-77,000 m^3 (10.6-20.3 million gallons) of acidic, metal-laden water (Smith, 2004).
- Acid Seeps: North Seep at 1.2 LPS (19 GPM (pH= 2.4; total acidity = 1,816 mg/L CCE, median values).
- Kill Zone: 3.7-ha (9-acre) area was devoid of vegetation and covered with acid salts.
- Sycamore Creek: 3.2 km (2 miles) were impacted with acidic water and metal precipitates.

Location of Cross-Section



Mine Pool and Main Acid Seep



Source: Modified from Smith, 2004.

Acid Seeps

Flow = 1.2 liters per second (19 gpm)

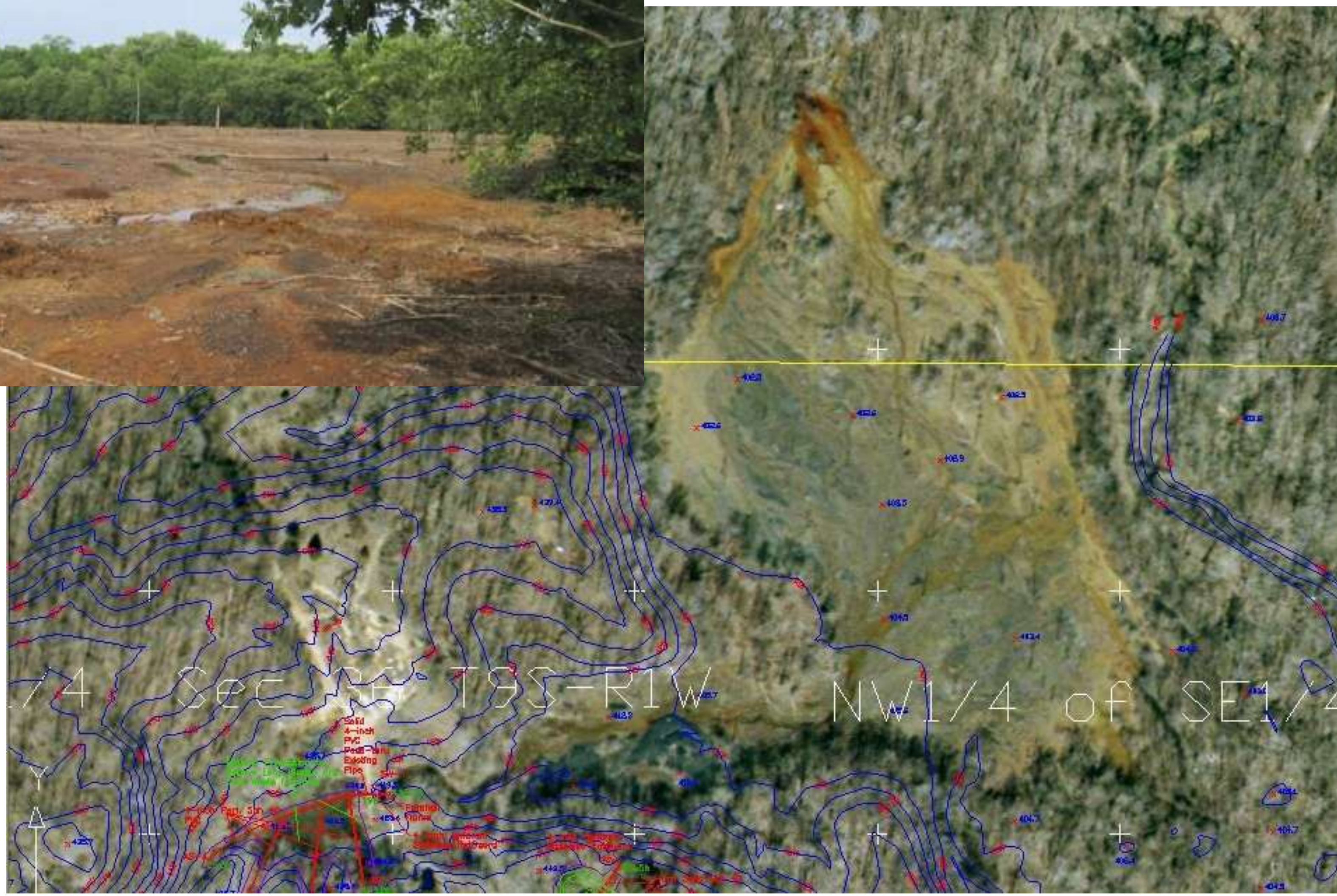
Baseline Data:

North Seep

Parameter	Value* (median)	Units
pH	**2.40**	
SpCon	**3,645**	*uS/cm*
D. Fe.	**389.3**	mg/L
D. Al	**123.2**	mg/L
Tot. Mn	**27.9**	mg/L
Tot. Acidity	**1,631**	mg/L CCE
Sulfate	**2,188**	mg/L

* Number of samples (n) = 8.

Problem ID: 3.7-ha (9-acre) “Kill Zone”



Sycamore Creek Impacts

Sycamore Creek prior to passive treatment system construction.

Downstream Sample Site

Parameter	Value* (low flow)
pH	2.92
SpCon	2,350
Tot. Fe.	109.0
Tot. Al	56.6
Tot. Mn	28.9
Tot. Acidity	705.97

* October 26, 2005

Timeline: AMD remediation at the Tab-Simco Mine Site

Collection of mine pool elevation data.

- 2005-2007: Site investigation and design Illinois DNR/Office of Mines and Minerals/OSM/ SIUC.
- Fall 2007: Passive treatment system designed and constructed.
- Winter 2007-Present: Post-construction evaluation.
- 2012: OSM awarded a cooperative agreement with SIUC.

Passive Treatment System Construction

- A major shortfall of the passive remediation technologies is the inability of providing long-term (> 10 year) treatment of drainage with high metal and Al (>20 mg/L) contents.
- Operational problems arise from plugging by precipitates, dissolution or coating of available carbonate minerals, and exhaustion of the organic carbon source.

Selected Solution: AMD Passive Treatment System

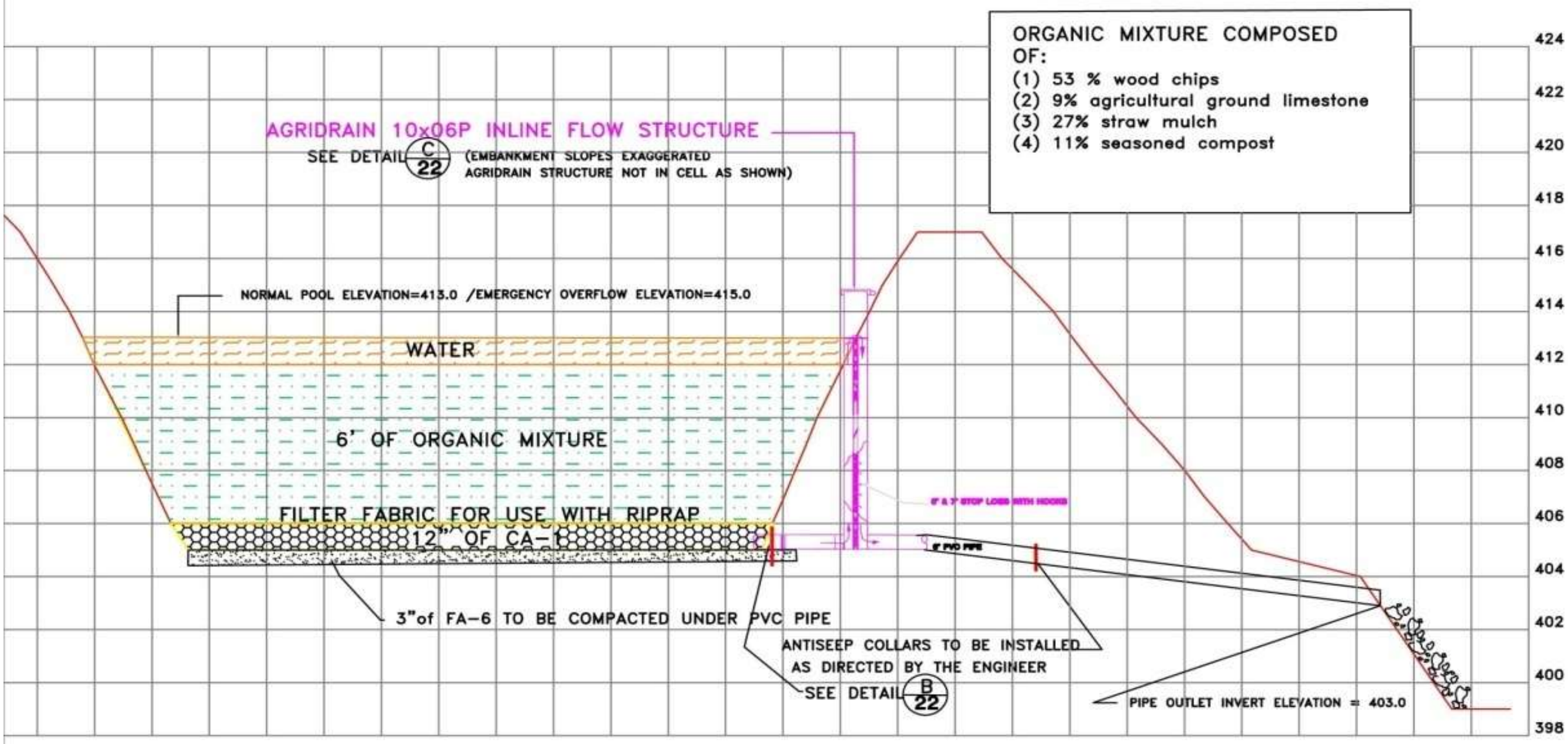
- Stage 1: The principle technology employed was a 0.3-ha (0.75-acre) Sulfate Reducing Bioreactor: Reduce sulfate, iron, and aluminum, add alkalinity and increase pH.
- Stage 2: Deep Oxidation Pond

  Oxidize remaining ferrous iron and store iron precipitates.
- Stage 3: Surface Flow Wetlands –

  Complete iron oxidation and precipitation.
- Stage 4: Open Limestone Drain –

  Aerate discharge and lower manganese levels.

Tab-Simco Bioreactor Cell Construction



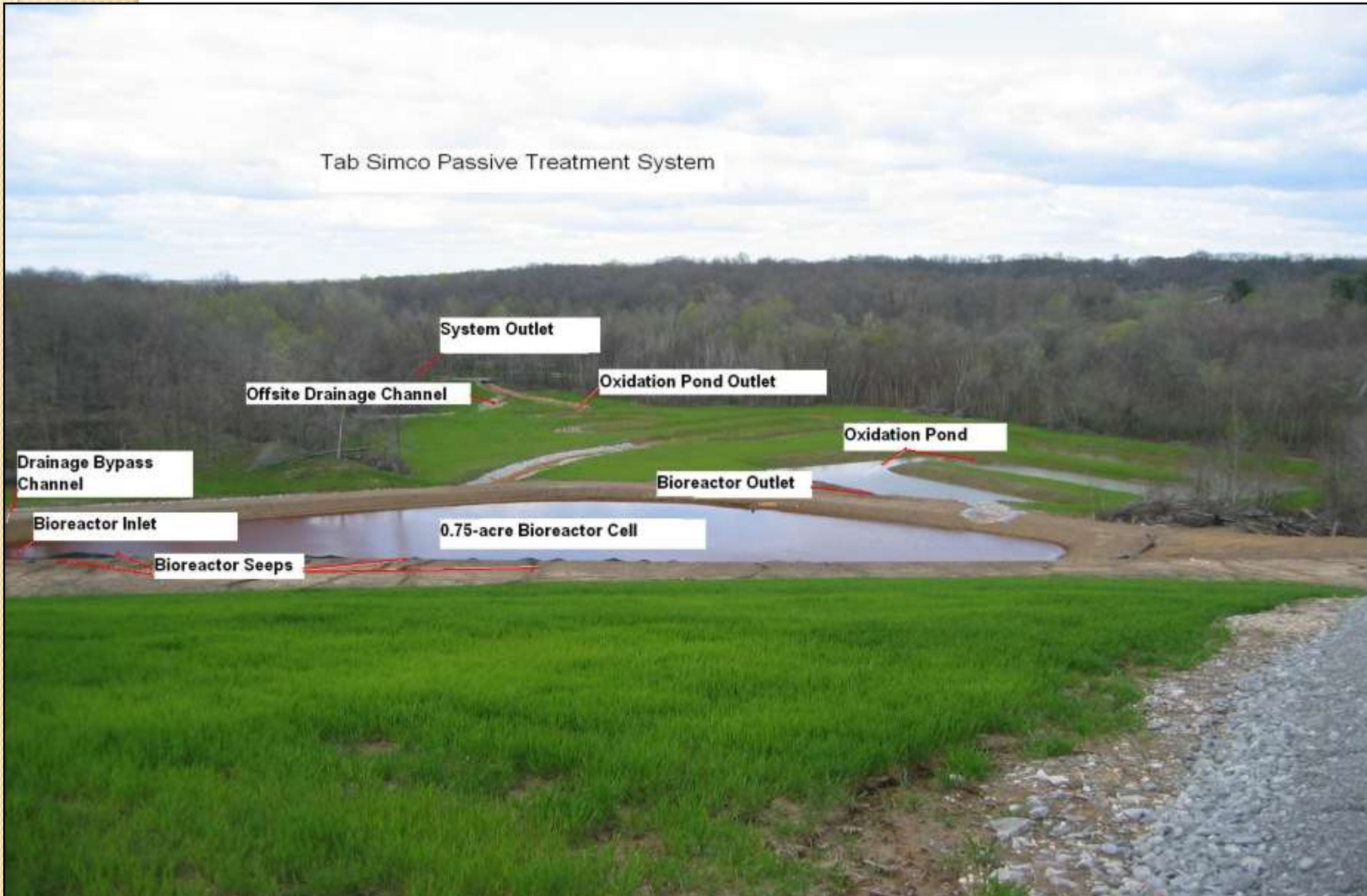
B 23 TYPICAL SECTION THROUGH ANEROBIC BIOREACTOR CELL

2007 Bioreactor Construction

Under Drain Construction

Compost Placement - 5,887 m^3 (7,700 cubic yards)

Tab-Simco AMD Passive Treatment System



Overview of the Passive Treatment System looking North from the edge of the Plateau.

Stage 1: Sulfate Reducing Bioreactor

- Reduce sulfate and iron; add bicarbonate (HCO_3^-) alkalinity – The principle processes are:
  - Anaerobic microbial sulfate reduction CH_2O representing biodegradable organic compounds).

$$2\ CH_2O + SO_4^{2-} \Rightarrow H_2S + 2\ HCO_3^-$$

  - Limestone dissolution.

$$CaCO_3 + H^+ \Rightarrow Ca^{2+} + HCO_3^-$$

- Bicarbonate neutralizes the acidity--raising pH and increasing the precipitation of metals such as Fe and Al.

$$HCO_3^- + H^+ \Rightarrow H_2O + CO_{2\,(aq)}$$

Stage 1: Sulfate Reducing Bioreactor - Metal removal processes.

- Hydrogen sulfide readily dissolves in water and combines with divalent metals (Me), such as Fe, Ni, and Zn, to form sulfide mineral precipitates MeS according to the following reaction:

$$H_2S_{(aq)} + Me^{2+} \Rightarrow MeS_{(s)} + 2\,H^+$$

- Adsorption of metals on clay minerals, metal hydroxides and organic matter within the bioreactor.
- Cation exchange reactions.

Sequestration of Metals: Iron

Discharge from the Tab Simco Bioreactor in 2008

Discharge of suspected FeS from the bioreactor; possible reaction within pond sediments:

$FeS + S \Leftrightarrow FeS_2$

(iron monosulfide*) (pyrite)

*Intermediate precursors such as Mackinawite [$(FeNi)_{1+x}S$] (where x = 0 - 0.11) and Greigite [$Fe(II)Fe(III)_2S_4$] are expected.

Stage 2: Deep Oxidation Pond

Stage 3: Surface Flow Wetlands

Goal:

Oxidize remaining ferrous iron and store iron precipitates;

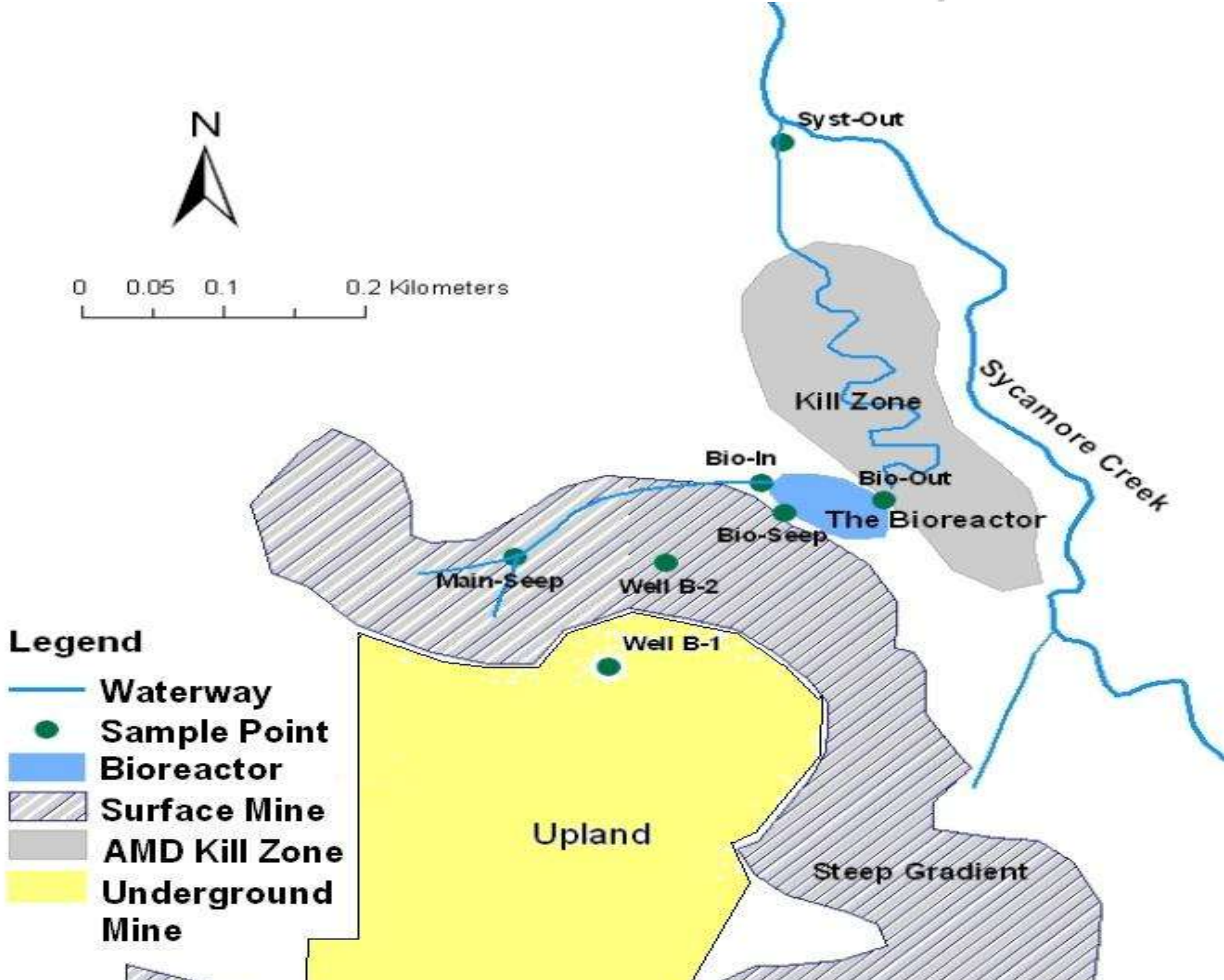
Tab-Simco Passive Treatment System

Possible reactions:

$Fe^{+2} + 3\ H_20 \Leftrightarrow Fe(OH)_3 + 3H^+$

$4\ Fe^{+2} + O_{2\ (aq)} + 10\ H_20 \Leftrightarrow 4\ Fe(OH)_3 + 8H^+$

Sample locations: Tab-Simco Passive Treatment System

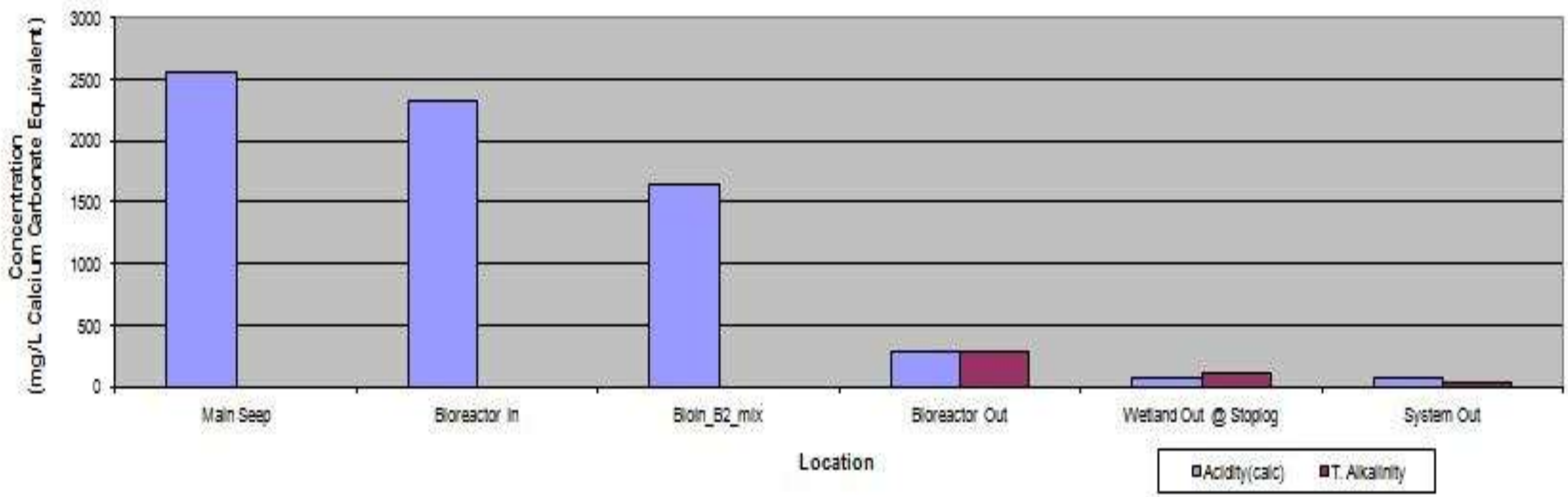


Performance Data: Tab-Simco Passive Treatment System, Illinois*

Site ID	pH	D. Fe	D. Mn	D. Al	D. Ni	D. Zn	Acidity	Alk.	SO_4
Main Seep	2.83	654.2	38.4	173.5	2.25	2.87	2,551	0	3,563
Bioreactor In	2.93	606.5	39.3	147.1	2.48	2.64	2,313	0	3,913
Well B2	2.85	287.3	34.6	98.2	1.33	1.92	1,306	0	2,373
Bioreactor In/B2 Mix	2.89	446.9	37.0	122.7	1.91	2.28	1,760	0	3,143
Bioreactor Out	6.34	113.0	32.5	0.85	0.07	0.12	275.8	289	2,099
System Out	5.79	6.80	24.6	0.96	0.16	0.25	71.0	27.3	1,691

*2007 through 2011; All values except pH are in mg/L; acidity and alkalinity (Alk.) are calcium carbonate equivalent values or CCE; acidity = calculated acidity.

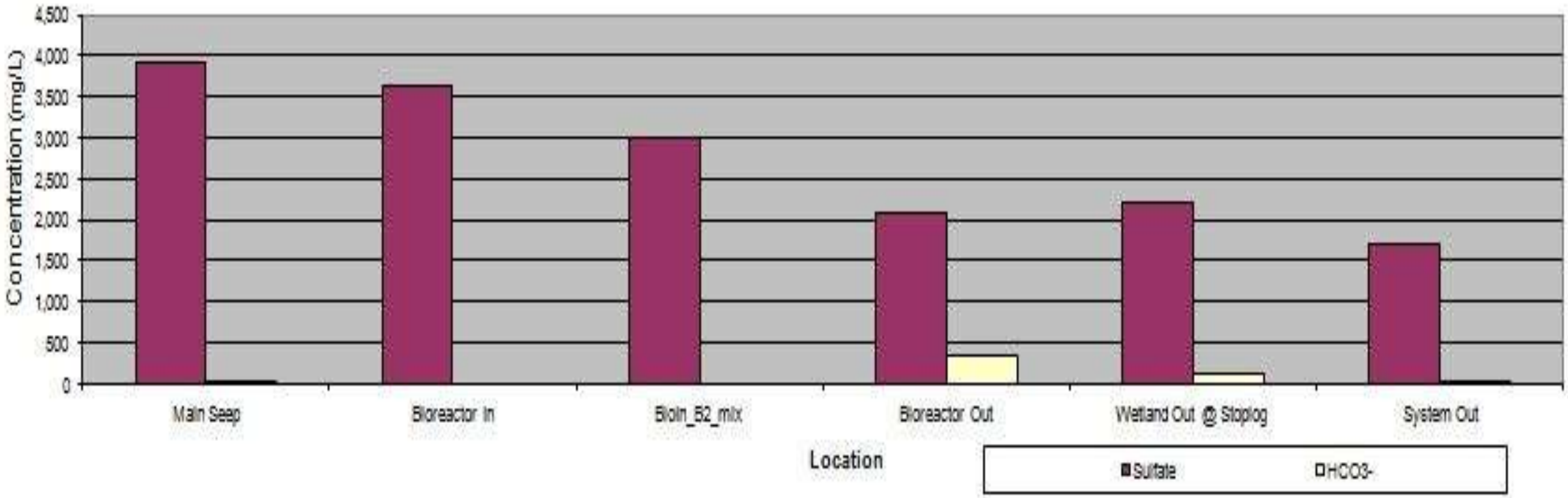
Changes in Acidity and Alkalinity



Acidity has dropped from a median 1,647 to 64.6 mg/L CCE, a 96.1% improvement.

Median Alkalinity at the bioreactor discharge is used to offset the remaining metal acidity.

Changes in Sulfate and Bicarbonate values within the Treatment System



The discharge remains a median of 1,750 mg/L.
Alkalinity generated by the bioreactor is used up in the oxidation structures.

Median Loading and Removal Rates

Site ID	D. Fe	D. Al	D. Mn	D. Ni	D. Zn	Cumulative Metals	SO_4
Bioreactor Loading* Rate(moles/m^3/day)	0.168	0.092	0.014	0.0007	0.0007	0.261	0.670
Bioreactor Removal Rate(moles/m^3/day)	0.120	0.091	0.0020	0.0006	0.0007	0.212	0.215
Removal (%)	71.2	99.3	14.0	96.3	94.7	81.2	32.1
Oxidation Cell Load Rate(moles/m^2/day)	0.148	0.083	0.0127	0.0005	0.0006	0.2321	0.6139
Oxy. Cell Removal Rate (moles/m^2/day)	0.160	0.090	0.0014	0.0005	0.0007	0.251	0.663
Cum. Removal (%)	99.9	99.2	36.2	89.8	89.5	99.6	42.8

*Bioreactor inlet channel and B2 mix.

Sulfate Removal (SIU, 2010 Study)

- 32.1% of the SO_4^{2-} is removed by the bioreactor cell (2008-2011). Process??
- $\delta^{34}S$ value of SO_4^{2-} increased in the bioreactor from an average value of 6.9‰ (inlet) to 9.2‰ (outlet), suggesting the presence of bacterial sulfate reduction processes (Segid, 2010).

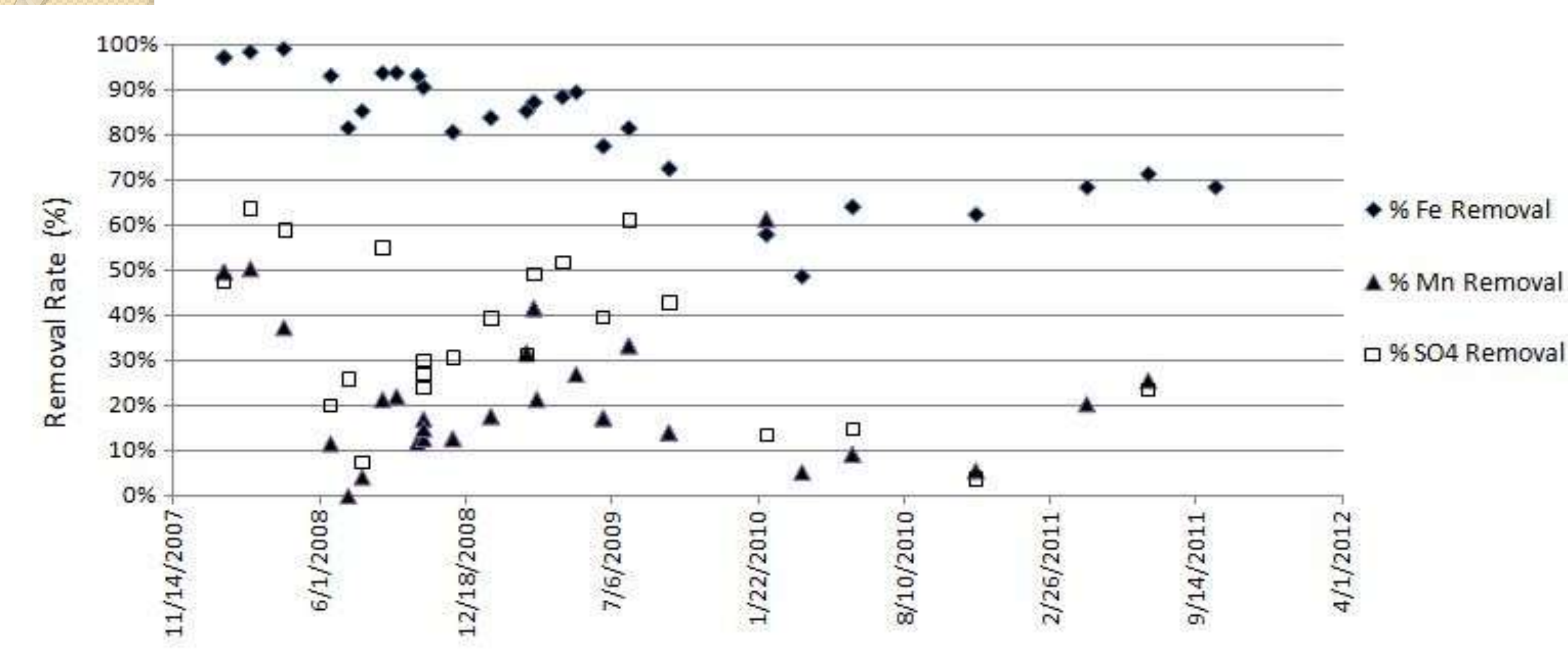
Sulfate Removal Rates - Summary

- McCauley *et al*. (2009) reported an average sulfate removal rate of 0.308 moles/m^3/day in bench tests.
- Gusek (2002, 2005) suggested a removal rate of 0.30 moles/m^3/day as a design criterion.
- Tab-Simco system is 0.215 moles/m^3/day, a value lower than the optimal rates. Detrimental factors include:
  - Undersized system due to site constraints.
  - Lower than optimum inlet pH (2.9).
  - High metal loading (Fe = 447 mg/L, Al = 123 mg/L).
  - Variable inlet chemistry (seasonal metal and sulfate changes).

Metal Removal Rates

- Reaction: $H_2S_{(aq)} + Me^{2+} \Rightarrow MeS_{(s)} + 2\ H^+$
- Suggests that for every mole of sulfate removed one mole of metals are also removed.
- The cumulative metal load of 0.26 moles/m^3/day is higher than sulfate a removal rate of 0.202 moles/m^3/day.
- A 2003 study by URS of a metal mine site recommended a lower cumulative heavy metal flux value of only 0.15 moles/m^3/day.

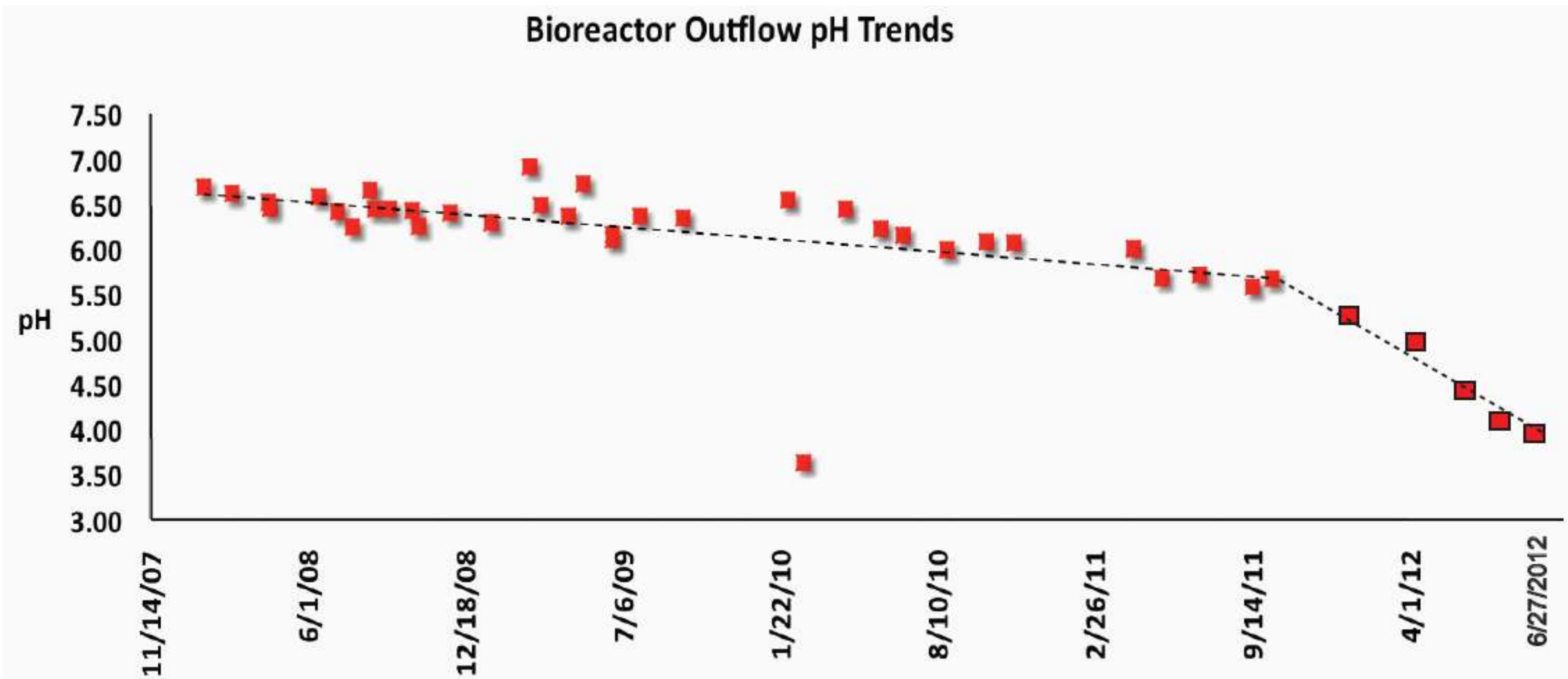
Sulfate and Metal Removal Trends in the Tab-Simco Bioreactor Discharge



Percent iron, manganese and sulfate removal declined in late 2009 but rebounded some in late 2010 .

SIUC Studies (OSM-funded):

Funded to study functional Bioreactor System Failed unexpectedly Winter of 2011.



Future SIUC Studies (OSM-funded):

- Bench Scale Studies: Investigate organic substrate options using six microcosms.
  - Evaluate seasonal variability of the above processes.
  - Evaluate aluminum removal mechanisms and geochemistry.
  - Conduct additional microbial community analysis.
- Tab-Simco Bioreactor Evaluation: Investigate the bioreactor failure by geochemical and biochemical studies of substrate.

Acknowledgements

- Dan Hause with the Reclamation Division of the Indiana Department of Natural Resources and Larry Lewis and Vinod Patel, Illinois Department of Natural Resources assisted in the system design.

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- Nick Grant and Joy Schieferstein, Office of Surface Mining, Mid-Continent Region assisted in the evaluation of the biologic impact of the system on Sycamore Creek.

- Landowners Mike Page and Carla and Treg Brown provided access to the property and allowed facility construction.

The End: Questions?